The Fraction of Pool Volume Filled with Fine Sediment in Northern California: Relation to Basin Geology and Sediment Yield

Final Report to California Division of Forestry and Fire Protection
August 20, 1993

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SUMMARY

Background: Forest and fish-habitat managers need new ways to analyze channel condition with respect to the supply of sediment in a stream channel and its capacity to flush it from the system. Indices of channel condition are needed to evaluate current cumulative effects so that unacceptable degradation of fish habitat can be avoided.

V*, the fraction of pool volume filled with fine sediment, was developed to fill this management need (Lisle and Hilton, 1992; Hilton and Lisle, in press). V* provides a measure of the in-channel supply of mobile bedload sediment. It is affected by sediment inputs and is related to the quality of fish habitat. V* is an unbiased measurement. Its variance in a reach of stream can be calculated and has been shown to be low enough to provide precise estimates of mean values with a reasonable amount of effort.

Purpose The purpose of the research supported by CDF and reported here is to expand the data base of carefully measured V* in northern California, relate V* to quantitative values of basin sediment yield, and explore geologic controls on V*.

Methods: Twenty-four reaches of streams in northern California and southern Oregon were added to the original set of eight studied by Lisle and Hilton (1992). Each channel had values for sediment inputs, or their basin had not had significant land use. Basins were chosen to include a variety of rock types. In each channel we measured V* in 6 to 22 pools, channel gradient, a longitudinal profile, and particle sizes of bedload deposits and fine sediments in pools.

Results:

1. Methods to measure V* have been improved. V* for individual pools can be computed in the field with a palm-top computer, so that the crew can adjust sample size to the desired confidence interval while still in the field. New methodologies are described in a publication (Hilton and Lisle, in press.)

2. V* increases with quantitative values of sediment yield per basin area among channels whose basins have lithologies (rock types) that produce moderate to high concentrations of fine sediment.

3. V* also varies with lithology. Those that produce moderate to high concentrations of fines (Franciscan and other soft or sheared sediments, weathered granite, schist) produce high background values of V* and show a strong response to sediment yield. Geologies with competent (hard) rocks

(high-grade metamorphics of Klamath Mtns, basalt, competent sandstone) produce low V* and show a weak response.

4. There is no apparent relationship between V* and channel size (third- to fifth-order channels) or channel type (step-pool vs bar-pool).

Recommendations and conclusions for V* as a channel-condition index:

1. V* is a sensitive index of the supply of mobile sediment in lithologies that produce moderate to high fractions of fines.

2. Values of V* for a channel should be interpreted by comparison with values from control (undisturbed) basins with the same lithology.

3. Variations with lithology do not complicate variations of V* in a particular reach, so V* can be readily used as a monitoring parameter.

4. V* is unbiased and well-grounded in statistics and sampling theory.

Related topics for further study:

1. Variations of V* over time

2. Relation to other channel-response variables

3. Using soil maps annotated by texture (percent gravel, sand, and finer material) to quantify effect of lithology on V*

4. Basin-wide variation of V* in relation to sediment inputs

Introduction

After a brief inspection, an experienced geomorphologist, hydrologist, forester, or fisheries biologist can gain an impression of the abundance of sediment in a stream channel and the stability of its bed and banks. However, practical and unbiased techniques for measuring these channel conditions have been lacking. Such techniques would enable land managers to evaluate cumulative effects on channel condition so that sediment-related degradation of fish habitat could be avoided and watershed restoration could be prioritized.

A fundamental principle of fluvial geomorphology is that a channel responds to sediment inputs by adjusting its bed elevation, width, channel pattern, geometry and roughness so that its capacity to transport sediment equals its supply (Mackin, 1948; Leopold and Bull, 1979). An initial response to increased inputs in a gravel-bed channel is a fining of the bed surface (Dietrich et al., 1989). This textural response has become the basis for at least three new indices of channel condition with respect to sediment supply: q* (Dietrich et al, 1989), Riffle Stability Index (Kappesser, 1993), and V* (Lisle and Hilton, 1992; Hilton and Lisle, in press; reported here).

To be successful, a channel-condition index should:

1. Accurately evaluate channel condition. The index should show a relationship with reliable estimates of sediment supply in the channel;

2. Be unbiased, statistically valid, and practical. The method should be free of operator bias, and standard errors and confidence intervals should be quantifiable using standard statistical theory. A few trained technicians should be able to complete measurements of a reach of channel in one or two days.

It is not the purpose of this report to compare the three indices according to these criteria. Instead, only V* will be examined.

V* is the fraction of pool volume filled with fine sediment (Lisle and Hilton, 1992; Hilton and Lisle, in press). It is a measure of the in-channel supply of mobile bedload sediment and is therefore related to basin sediment yield or input rates. Lisle and Hilton (1992) and Knopp (1993) show good correlations between V* and semi-quantitative evaluations of sediment supply.

V* is designed to be free of operator bias. Its variance in a reach of stream can be calculated and has been shown to be low enough to provide good estimates of mean values (Lisle and Hilton, 1992). Within a reach, the volume of fine sediment is strongly correlated with pool volume, but in some channels V* can be weakly correlated with pool size and local stream gradient.

The purpose of the study reported here was to expand the data base of V* measurements in northern California, relate V* to quantitative values of basin sediment yield, and explore geologic influences on V*. Refinements in the method allow in-the-field calculation of V*, and V* remains an unbiased and statistically robust parameter. V* can be quantitatively related to sediment inputs to channels. However, lithologic controls of the fraction of fine sediment introduced to channels can cause strong differences in V* between basins underlain by different rock types. These results are detailed and implications for V* as a management tool are discussed.

Methods

Twenty-four channels in northern California and southern Oregon were chosen for study (Table 1). Each channel had data for inputs of bedload sediment, or their basins had no significant land-use history. The latter were included to provide background values of V* for various lithologies (rock types). A variety of lithologies were investigated (Table 1). All channels were single-thread, gravel-bed channels. Reaches were chosen to be less confined and have lower slopes than adjacent reaches in order to focus on the most responsive reaches in a drainage system. No significant additional sources of sediment or streamflow lay within a study reach. Drainage areas ranged from 3.8 to 520 km^2; stream gradients ranged from 0.0026 to 0.044.

We did field work in summer, 1992. We measured fine-sediment and residual-pool volumes (Lisle, 1987) in 6 to 22 pools in each reach, depending on on-site computations of average V* and its variability. We measured all pools in a designated reach that met the following criteria:

1. Maximum residual depth greater than two times the riffle-crest depth.
2. Essentially horizontal water surface at low flow
3. Includes most of the channel, including the thalweg

We also surveyed longitudinal thalweg profiles (from which gradient was measured), and sampled pool-fill material and bedload deposits.

We utilized a palm-top computer with a Lotus 1-2-3 spreadsheet to compute values of V* on-site. In this manner, mistakes in measuring and recording data can be caught and corrected before leaving the field. Also by computing V* as pools are measured, we can evaluate its variability and estimate the number of pools needed to obtain an accurate mean value for the reach. We also developed methods to randomize measurements of fine-sediment and water depth. New methods and computational programs are given in Hilton and Lisle (in press).

Results

Variance of V*

V* was measured repeatedly in some pools to evaluate the error in measurement. The coefficient of variation (ratio of standard deviation to the mean value) was approximately 20% in reaches where V*>0.1 (Figure 1, from Hilton and Lisle, in press); it was much greater in reaches with lower values of V*, but large confidence intervals are acceptable where volumes of fine sediment in pools are insignificant to aquatic ecosystems.

The variance of V* within a reach varies with channel complexity. Large woody debris (LWD) and other roughness elements in pools tend to trap more fine sediment and increase the variance of V* between simple and complex pools. (Practitioners in Washington exclude pools that contain LWD in order to reduce variance (David Montgomery, pers. communication, 1993, Seattle).) For most channels with mean V*>0.1, ten or fewer pools are required to limit the standard error of mean V* to 20% (Figure 2, from Hilton and Lisle, in press); complex channels and those with V*<0.1 may require more than twenty pools, although again a wider confidence interval can be tolerated for low values of V*.

Given a reasonably acceptable confidence interval, enough pools can be sampled in a short period to make V* a viable management tool. It takes a trained crew of three approximately one hour or less to carefully measure V* in most pools, and thus most reaches can be sampled in one or two days.

Relation of V* to Sediment Yield and Lithology

We found that the greatest problem in relating V* to sediment load is the uncertainty and inconsistency in quantifying load from a variety of sources of data. Although bedload is the relevant particle size, sediment-input data are rarely broken down by size. The sediment supply for a reach at a particular time is difficult to evaluate from measurements of sediment yield measured for a period of years. Sediment inputs (landslides, etc) are highly variable in space and time, and with our available knowledge, we do not know how they propagate downstream and combine to constitute the load of a reach of stream at some time after the inputs were measured. Data from different sources cover different time periods, and the timing of major inputs varies from stream to stream (Table 1).

In the first analysis, we dimensionalize total sediment yield or input rate ($Mgkm^{-2}yr^{-1}$) by background yields ($Mgkm^{-2}yr^{-1}$) that have been measured in pristine basins of similar geology (Table 2). V* shows a positive correlation with relative sediment yield over three orders of magnitude (Figure 3). However, lithology apparently has a strong influence on V*. Lithologies that produce high concentrations of sand and fine gravel (weathered granite, soft and sheared Franciscan sediments, and schist) show high background levels of V* (0.1-0.2) and higher values (>0.25) that are associated with high sediment yields. Lithologies that produce low concentrations of fine sediment (volcanic rocks and competent metamorphics and sandstones) show low values of V* (<0.05) and no increase with yield, although high yields for these lithologies are not well represented.

In order to compare V* values from pristine streams with those from streams with sediment yield data, sediment yield values from the other streams were categorized according to orders of magnitude: low (<100 $Mgkm^{-2}yr^{-1}$); moderate (100-1000 $Mgkm^{-2}yr^{-1}$); and high (>1000 $Mgkm^{-2}yr^{-1}$). This created a qualitative basis for comparing all streams (Figure 4). V* for pristine streams plot similarly to those for low-yield streams, and again V* for lithologies that produce abundant fine sediment plot higher than those that produce little fine sediment.

Influence of Channel Size and Morphology

Although streams were not selected for this purpose, an initial examination using our data shows no apparent effects of channel size and morphology on V*. There are no apparent distinctions in V* between channels with drainage areas from 4 to 520 km^2 (Table 1).

Each pool was classified as bar-pool (associated with bends and alternate bars, typically in low-gradient segments) or as plunge- or step-pool (downstream of a sharp drop over LWD or boulders, typically in high-gradient segments). To explore the effect of pool morphology on V*, the value of V* for each pool was divided by the mean for the reach, and values from all reaches were compiled. These normalized values of V* were then segregated according to pool type and compared. There were 184 bar-pools and 64 plunge- and step-pools. Normalized values of V* were not significantly different between these two populations ($p=0.70$; Student's t-test).

Relation to Habitat Condition

Although we have not quantified any relations between V* and other habitat conditions or biotic factors, the existence of these relations is apparent. For example, a loss of 25% of pool volume to filling by fine sediment may not by itself seem significantly harmful to fish habitat considering the high variability of pool volume, but according to our observations a V* value of this magnitude is associated with obvious unfavorable substrate conditions. Embeddedness (the degree to which the armor layer is inundated with fine sediment) would likely be high everywhere but in steep riffles and cascades, and sediment concentration during stormflows and rates of infiltration of fine sediment into spawning gravels can also be expected to be high. Channels with V* values of about 0.10 have noticeable concentrations of fines on their bed surface which may be at a threshold of concern. Those with V* less than 0.05 could be considered free of fine-sediment problems. However, since aquatic ecosystems evolve under different hydrologic and geologic conditions, any recognizable threshold-of-concern values of V* can be expected to vary from region to region. Research needs to be directed specifically at these relationships.

Conclusions and Recommendations

V* as an Index of Channel Condition

V* appears to meet the criteria for an effective channel-condition parameter as stated in the introduction, although further research would be warranted.

First, V* is a sensitive index of the supply of mobile sediment in geologies that produce moderate to high fractions of fines. V* is also apparently related to the health of aquatic ecosystems, but this relationship has not been investigated. It may provide a quantitative link between watershed condition affecting stream channels and aquatic ecosystems.

Quantitative relations between V* and sediment inputs to stream channels have been demonstrated, but for a given rate of input, V* tends to be relatively high in basins whose lithologies produce high concentrations of sand and fine gravel. Interpretations of V* for channel mobility and sediment supply should therefore be indexed to geology. Interpretations are aided by having values for control (undisturbed) basins in the same geology as that of the target basin.

Insofar as organisms respond to fines, some basins appear more sensitive to increased sediment than others. At this point, however, relationships between V* and aquatic habitats and organisms are poorly defined. Likely ecologically based thresholds of concern for V* would probably fall between 0.1 and 0.2, depending on geology. Fines-rich lithologies may tend to have higher thresholds because their ecosystems would be better adapted to higher background levels of fine sediment, but higher V* values would also tend to be more common than in fines-poor lithologies. Fines-poor lithologies may tend to have lower thresholds because V* values that are low relative to fines-rich lithologies but high relative to background values of fines-poor lithologies may signal the potential for other sediment impacts such as channel instability, bank erosion, aggradation, and pool filling by unsorted bedload.

This speculative discussion highlights the need for (1) research on relationships between V* (and other channel-condition indices) and aquatic habitats and organisms to establish ecologically based thresholds of concern;

and (2) further development of other channel-condition indices to fit a variety of geomorphic conditions (e.g., lithology, channel type and size) and possible impacts (e.g., sediment inputs of different particle size, changes in runoff or woody debris) on ecosystems. No single index will likely satisfy every situation, given the variety of ways sediment inputs and high runoff events can affect channels in different geomorphic environments. Each index should meet the two criteria listed in the introduction.

V* as a Monitoring Parameter

Variations with geology do not complicate variations of V* in a particular reach, so V* can be an effective monitoring parameter, especially where background values of V* are relatively high (say, 0.1 or greater). V* can be expected to remain constant from year to year as long as the balance between sediment supply and runoff remain the same. We have not had the opportunity to follow meaningful annual trends in V* because we began measuring V* during the California drought. However, preliminary results from annual measurements carried through this summer (following a normal winter of high runoff) show little change in V* in most channels and signicant increases or decreases in a few.

V* is an unbiased, statistically sound, and practical method. Using a palm-top computer, one can compute V* in the field (Hilton and Lisle, in press). Variability between pools can then be evaluated and sample size increased or decreased accordingly before leaving the site. A mean value with a small standard error can be measured in less than a day to two days.

Table 3 compares V* with q* and the Riffle Stability Index with respect to sources of bias, time requirements, and sample sizes commonly used to measure a mean value. V* compares favorably with q* in terms of bias and Riffle Stability Index in terms of time requirements and shows advantages over either in the remaining category. The commonly used sample size for V* is larger than that of the other two parameters; this may produce a smaller standard error, but this has not been determined.

Recommendations for Further Research

1. Variations of V* over time. V* can be expected to vary as the balance between sediment supply and transport power varies. Although the degree of annual variability of V* in a stable watershed can be expected to be low, ranges in variability under different watershed conditions are not known.

2. Relation to other channel-response variables. V* can be expected to correlate with other channel-mobility parameters, e.g., q* and dimensionless boundary shear stress, but these parameters measure different aspects of mobility. Examining where various parameters do and do not correspond should indicate where they are most appropriate and provide some new insights into channel mobility.

3. Evaluating fines concentration of inputs from soil texture. Soil maps annotated by texture (percent gravel, sand, silt, etc), when combined with locations of sediment sources would provide the basis for quantifying the relation between V* and lithology. If this relationship were known, background values for V* could be evaluated in a variety of landscapes without relying on the rare pristine watersheds that have sediment-budget data.

4. Basin-wide variation of V* in relation to sediment inputs. Before now, we have had no practical method to evaluate sediment supply at points in a channel system. Spatial distributions of V* values and sediment inputs would help to decipher how sediment moves through a drainage system. With this knowledge we would be better able to predict the magnitude, timing, and duration of sediment-related impacts from upstream. This remains one of the biggest stumbling blocks in evaluating and predicting cumulative watershed effects.

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Table 1. V*, drainage area, stream gradient, lithology, and sediment yield of streams used in this study.

Creek, Main Stem	V*	Drainage Area (km2)	Stream Gradient	Lithology[a]	Sediment Yield (Mg$km^{-2}yr^{-1}$)
Bald Mtn, Elk	0.074	18.6	0.024	CSS	44.3 (landslides, 1973-1986)[b]
Big French, Trinity	0.040	99.0	0.019	HM	pristine
Blackwood, Lake Tahoe	0.075	29.5	0.015	CSS	101 (total), 21 (BL), 1975-1985[c]
Bridge, Redwood	0.24	28.3	0.012	SCH	630 (total), 1954-1981; 71 (total from landslides=~half of total inputs), 1970-1978[d]
Clear, Klamath	0.045	154	0.016	HM	pristine
Crapo, Salmon	0.23	44.5	0.040	DG	1360[e]
Decker, SF Eel	0.12	5.2	0.024	FR	pristine
Elder, SF Eel	0.089	16.9	0.022	FR CSS	pristine
General, L Tahoe	0.13	18.6	0.016	DG	49 (total), 31 (BL), 1981-1987[c]
Grass Valley, Trinity	0.50	80.0	0.017	DG	1500-2200[f]
Grouse, SF Trinity	0.26	140	0.016	FR SCH	1500, 1960-1988; dominated by 1964 flood[g]
Horse Linto, Trinity	0.12	97.0	0.018	HM SCH	pristine
Jacoby, Humboldt Bay	0.14	36.3	0.0063	FR	160 (total); 14 (BL)[h]
Knownothing, Salmon	0.038	58.1	0.020	HM	124[e]
Little Lost Man, Redwood	0.21	9.0	0.045	FR	63 (total), 13 (BL), 1975-79[d]
LNF Salmon	0.046	50.2	0.028	HM DG	14.2[e]
Nordheimer, Salmon	0.029	81.3	0.016	HM	13.1[e]
NF Caspar	0.21	5.0	0.013	FR	224, 1963-1976; 1980-1988[h]
Plummer, Salmon	0.038	37.8	0.036	HM	18.4[e]
Purple Mtn, Elk	0.049	3.8	0.035	CSS	2.6 (landslides, 1973-1986); Much lower than apparent yield from failing banks and ravelling slides today. Most slides formed 1957-1964[b].
Red Cedar, Elk	0.027	7.0	0.016	CSS	pristine; debris torrent ends upstream of reach.
Sage Hen, Feather	0.041	18.3	0.015	V	nearly pristine
SF Caspar	0.28	5.4	0.012	FR	289 (1963-1976)[h]
SF Salmon	0.090	88.3	0.028	DG	5.5[e] underestimated because doesn't include erosion from fine-grained streamside slides.
Taylor, Salmon	0.109	27.9	0.037	DG	18[e]

a:CSS=competent sandstone; HM=hard metamophics; V=volcanics; FR=Franciscan soft sediments; SCH=schist; DG=weathered granite

Sources of data: b=Siskiyou National Forest, Gold Beach, OR; c=USGS, Menlo Park; d=Redwood National Park, Arcata; e=landslide volume + surface erosion, 1975-88, Klamath National Forest, Yreka; f=Soil Conservation Service, Redding; g=Six Rivers National Forest, Eureka; h=Redwood Sciences Lab, Arcata

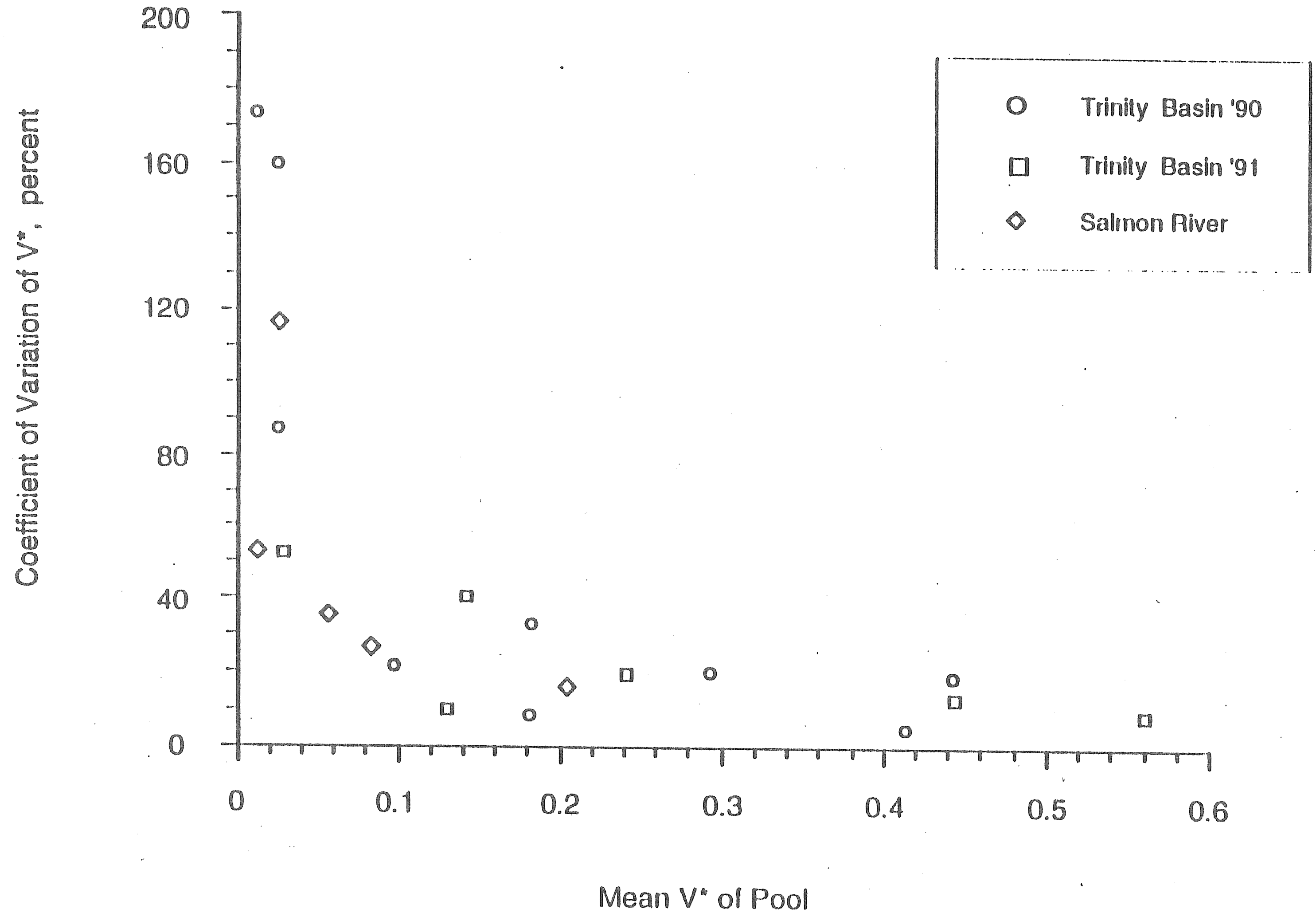

Figure 1. Variability of the estimate of V* from multiple measurements. The coefficient of variation is the ratio of standard error of the mean to the mean value of V* for each set of measurements.

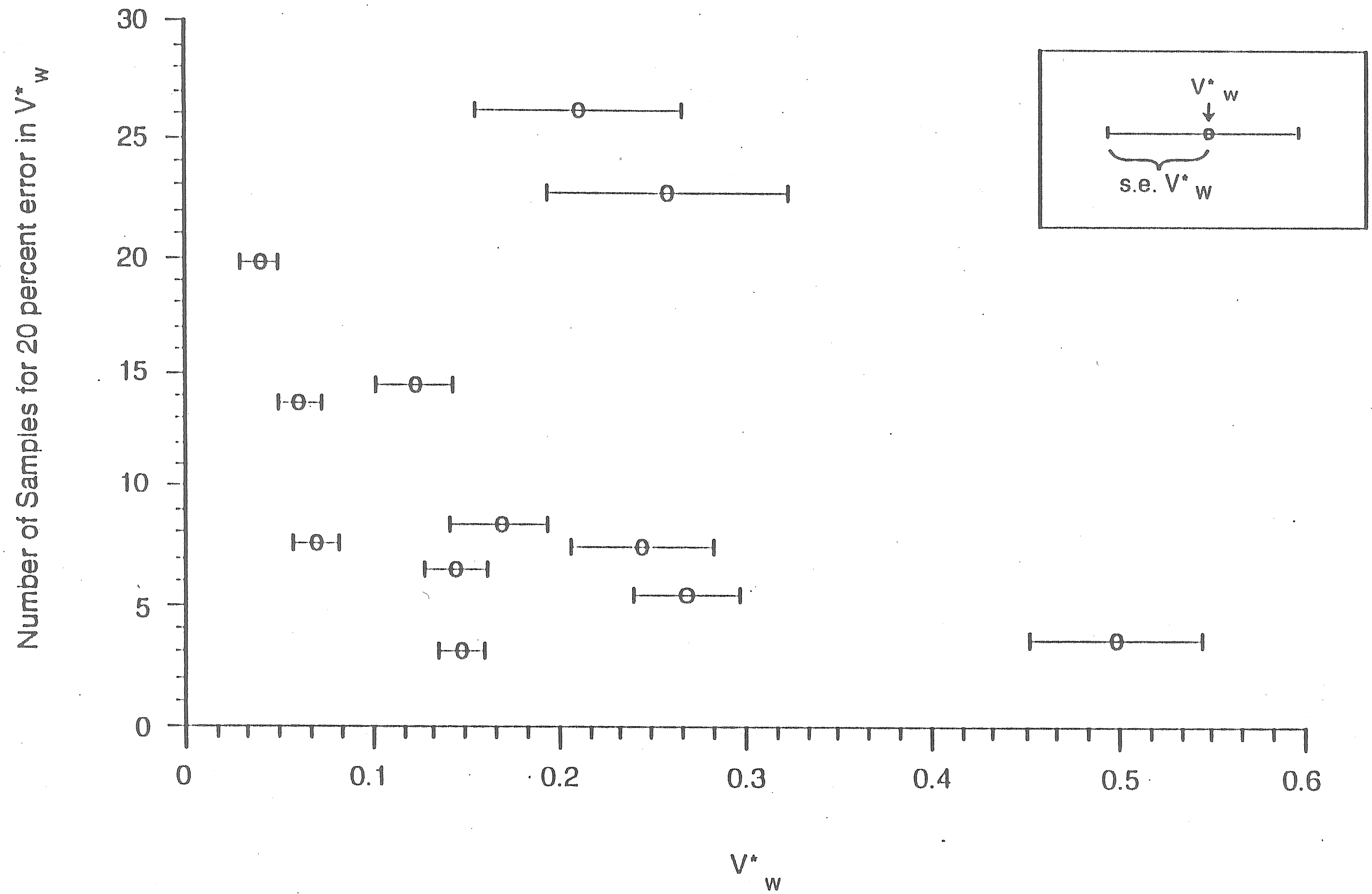

Figure 2. Predicted sample sizes necessary to limit the error in mean V* to 20 percent.

Table 2. Sediment yield from pristine basins underlain by various lithologies in California, Oregon, and Idaho.

Lithology/Basin	Drainage Area (km2)	Annual Sediment Yield (Mg/km2)	Period of Record	Source
Plutonics:				
Silver Cr, Payette R, ID	0.3-6.6	6.4	1961-74	Megahan (1976)
General Cr, L. Tahoe Basin	19	49	1980-85	USGS, Menlo Park
SF Salmon R, CA	88	6.6	1944-88	Klamath NF
Teakettle #7, Kern R, CA	0.2	23	1938-60	Dendy and Champion (1973)
mean		21		
Volcanics:				
Onion Cr, American R, CA	0.5-2.1	30	1957-60	Dendy and Champion (1973)
HJ Andrews #2, 8, 9, OR	0.1-0.6	15	1958-88	Grant and Wolff (1991)
mean		22		
Metamorphics:				
Teakettle #2, 2A, 3	0.7-2.2	11	1938-65	Dendy and Champion (1973)
Plummer Cr, Salmon R, CA	38	24	1944-88	Klamath NF
mean		17		
Franciscan:				
Little Lost Man Cr, RW Cr	9.0	63	1975-79	Tally (1980)
Hayes Cr, Redwood Cr, CA	1.5	18	1975-79	Janda (1977)
NF Caspar Cr, Jackson SF, CA	5.0	290	1963-76	Rice, Tilley and Datzman (1979)
mean		120		

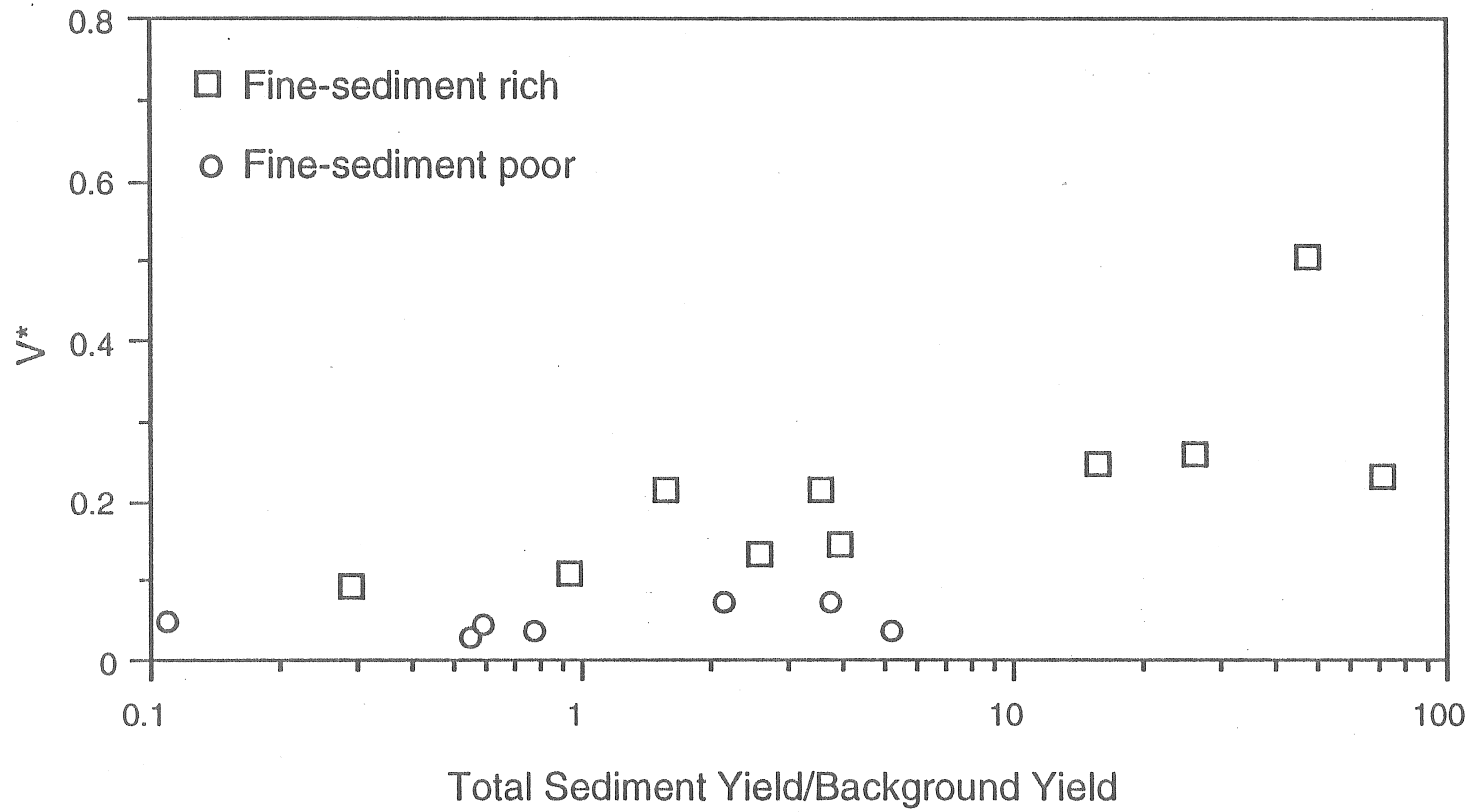

Figure 3. Mean V* for a reach vs. total sediment yield per unit area divided by background yield for corresponding hydrologic and geologic conditions.

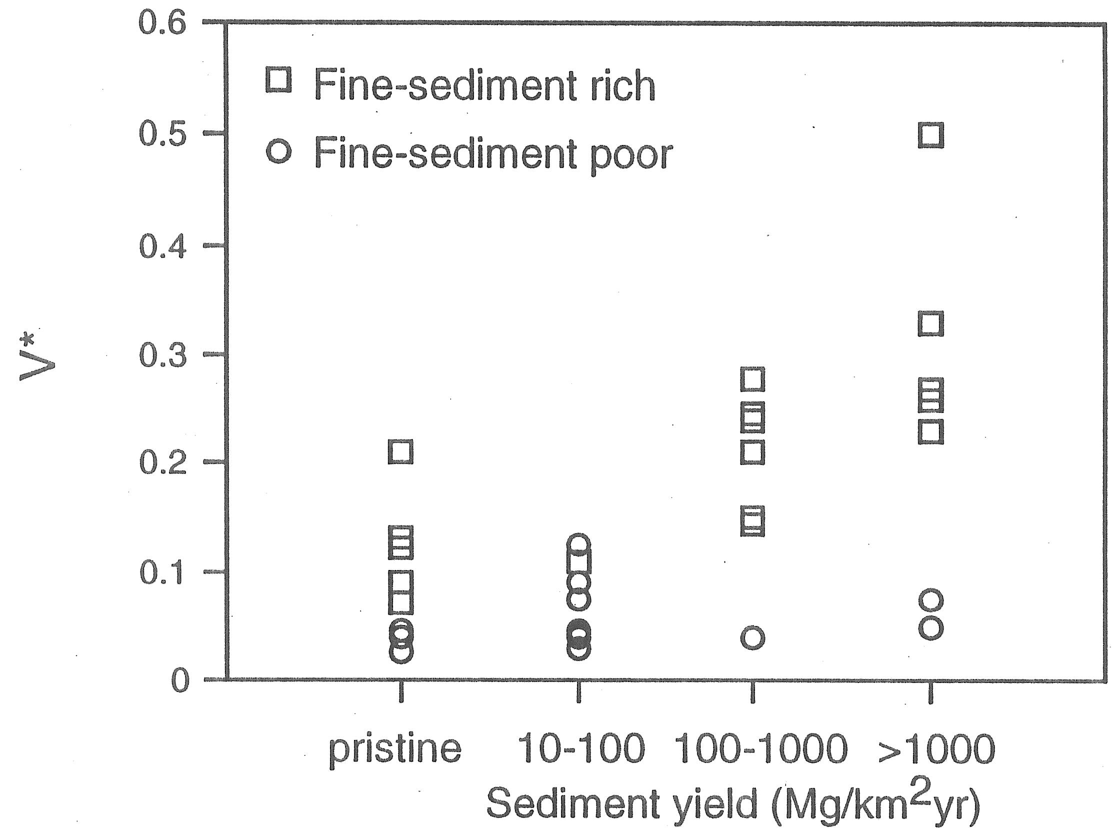

Figure 4. Mean V* for a reach vs. sediment yield category.

TABLE 3. Sources of bias (judged by this author), days required to complete measurements, and commonly used sample size of V*, q* (Dietrich et al, 1989; Kinerson, 1990), and Riffle Stability Index (Kappeser, 1992).

Parameter	Sources of bias	Days Required	n
V*	Low--Distinguishing fine sediment from underlying armor layer	1-2	6-15
q*	Low--Determination of bankfull shear stress; choice of study reach	>2	2-4
Riffle Stability Index	High--Identification of largest size transported at bankfull stage	<1	3